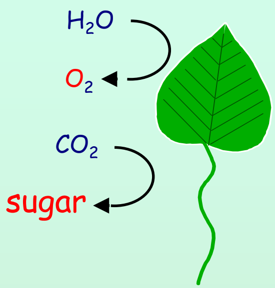
Solar Energy Utilization

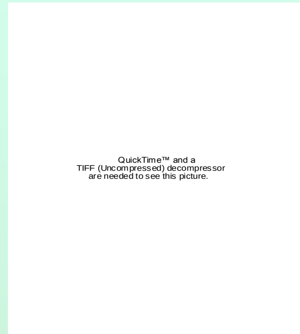
Solar Electric

.001 TW PV
$0.30/kWh w/o storage

1.5 TW electricity
$0.03-$0.06/kWh (fossil)



natural
photosynthesis

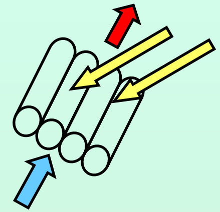


Solar Fuel

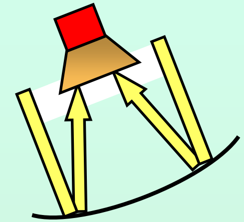
1.4 TW solar fuel (biomass)

11 TW fossil fuel
(present use)

~ 14 TW additional energy by 2050



50 - 200 °C
space, water
heating



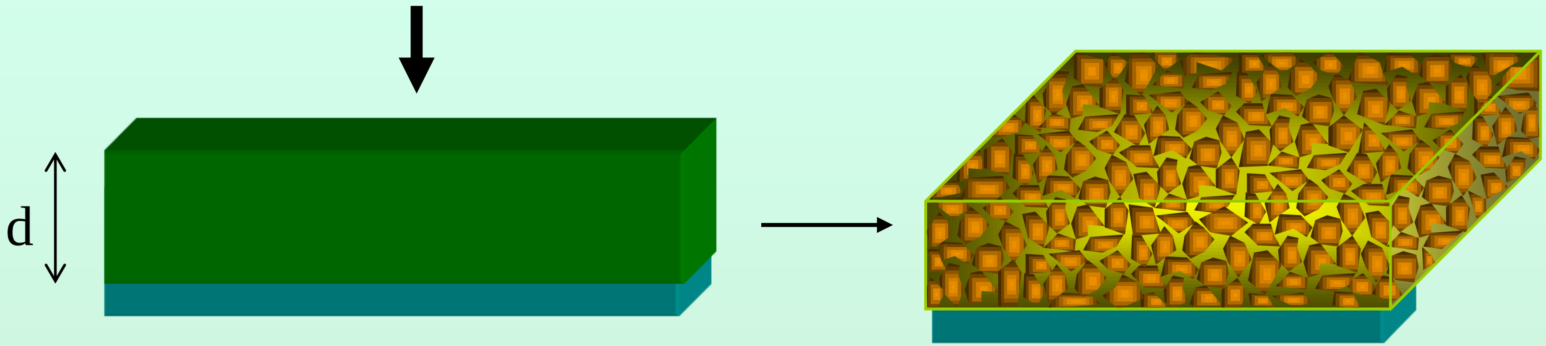
500 - 3000 °C
heat engines
electricity generation
process heat

Solar Thermal

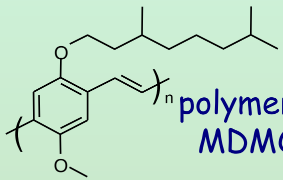
0.002 TW

2 TW
space and water
heating

“Solar Paint”

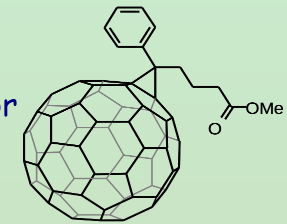


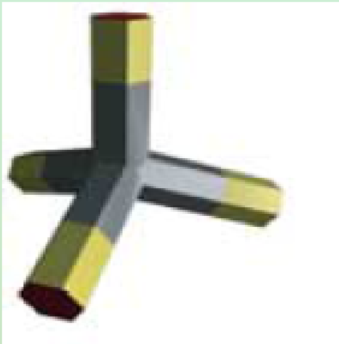
“Fooling “inexpensive particles into behaving as single crystals

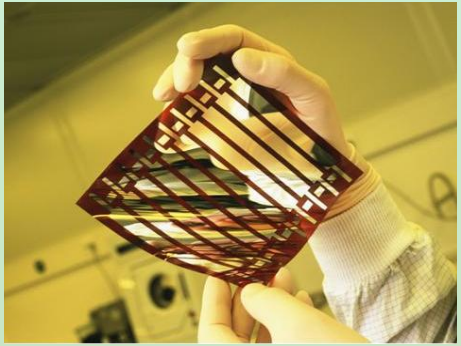


polymer donor
MDMO-PPV

fullerene acceptor
PCBM



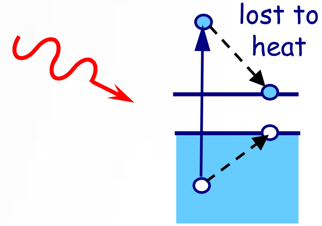


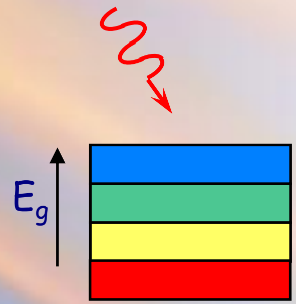


inexpensive processing, conformal layers

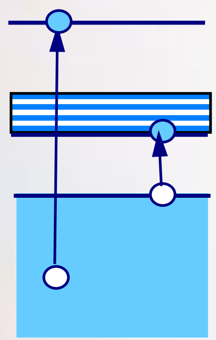
Revolutionary Photovoltaics: 50% Efficient Solar Cells

present technology: 32% limit for
- single junction
- one exciton per photon
- relaxation to band edge

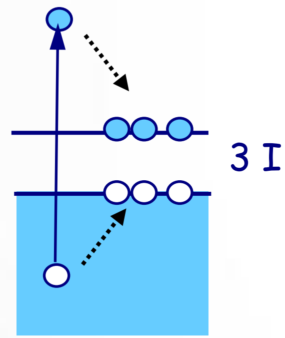




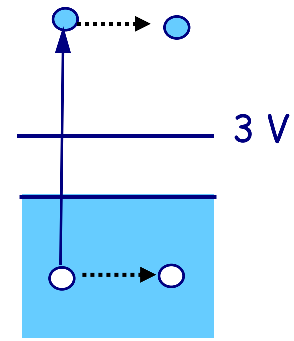
multiple junctions



multiple gaps



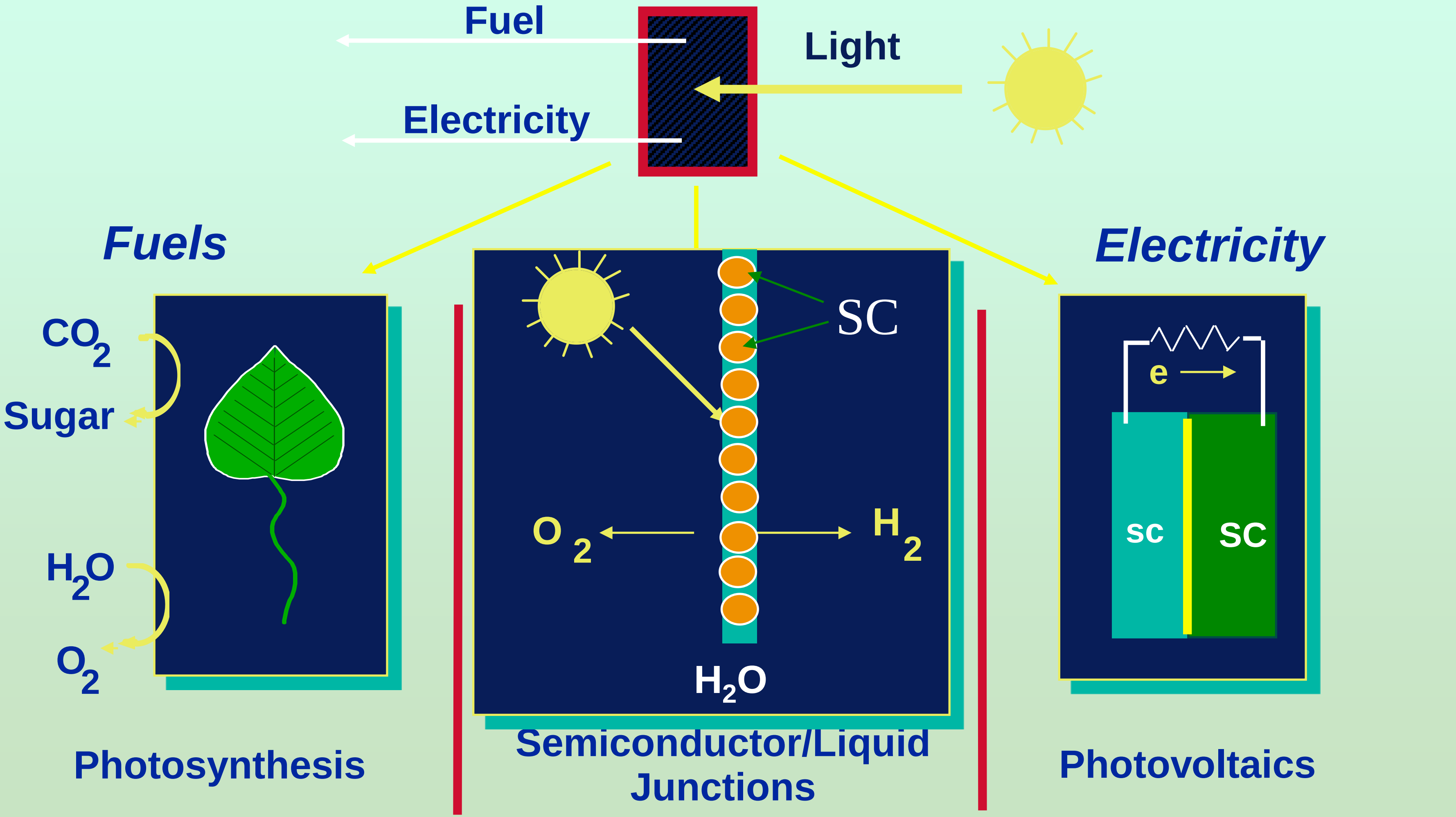
multiple excitons per photon



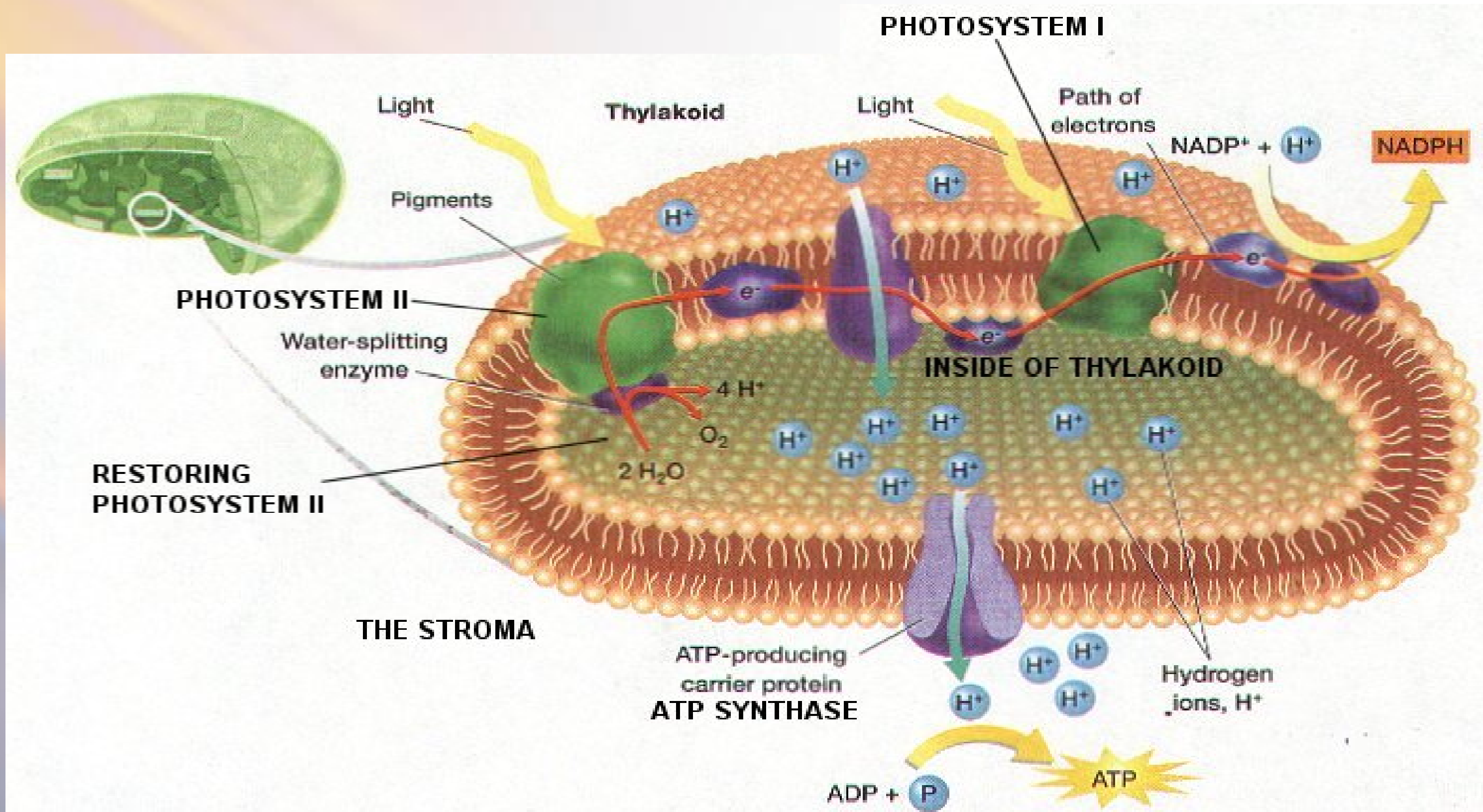
hot carriers

rich variety of new physical phenomena
understand and implement

Energy Conversion Strategies



Lessons from Photosynthesis



Report of the Basic Energy Sciences Workshop on Solar Energy Utilization

Nanorod-based Membrane Offers Several Advantages

Tandem junction system

Increased light absorption

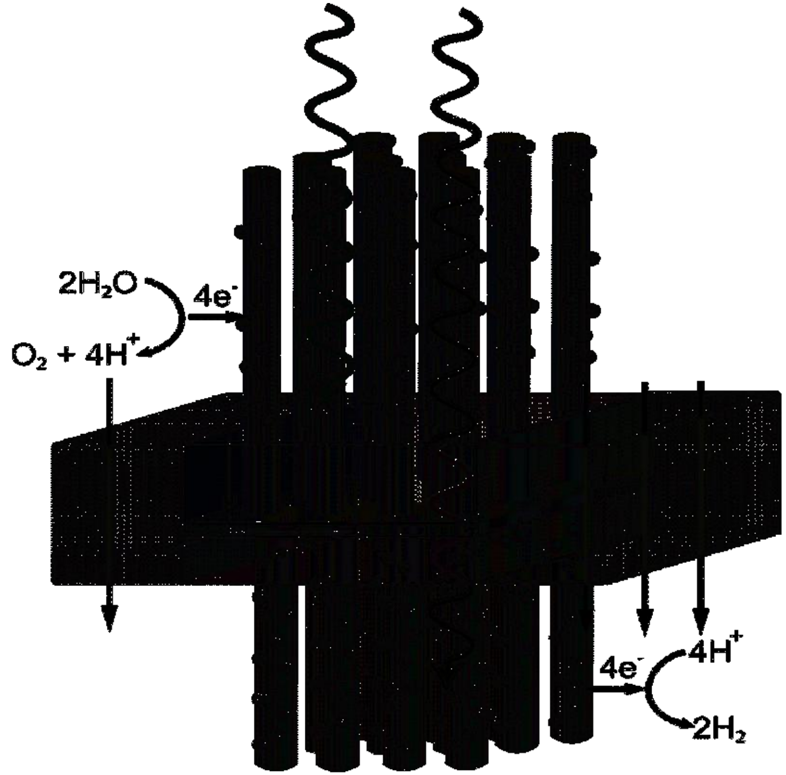
Nanorod geometry orthogonalizes directions of light absorption and carrier collection

Long nanorods can absorb all incident light

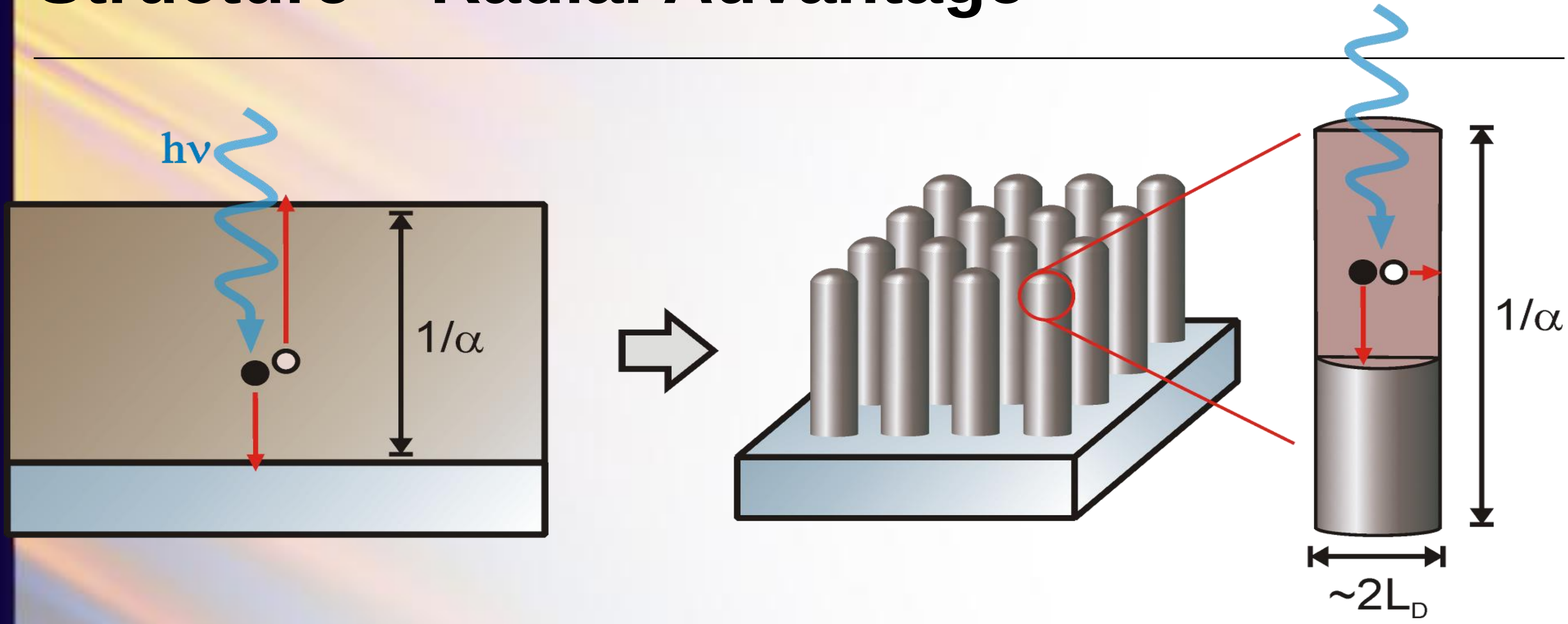
Carriers need only travel radially to the nanorod sidewalls to be separated and collected

Greater flexibility in materials selection

Potential candidates: WO_3 and Si



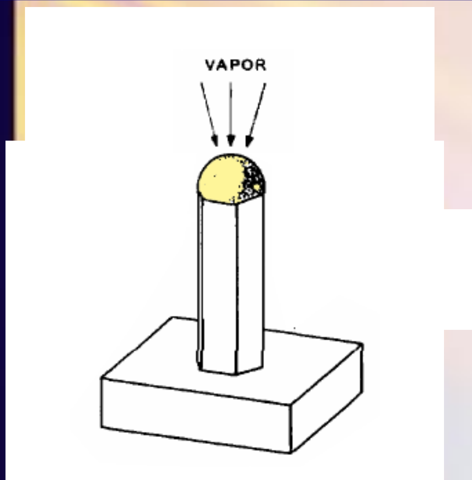
Structure – Radial Advantage

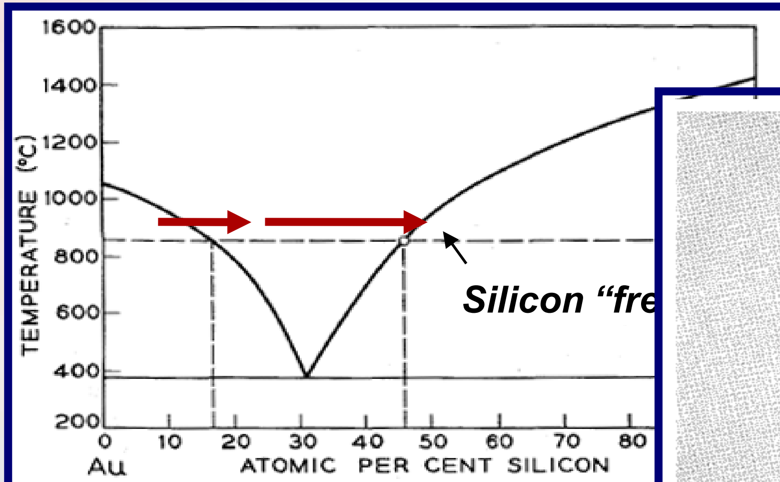


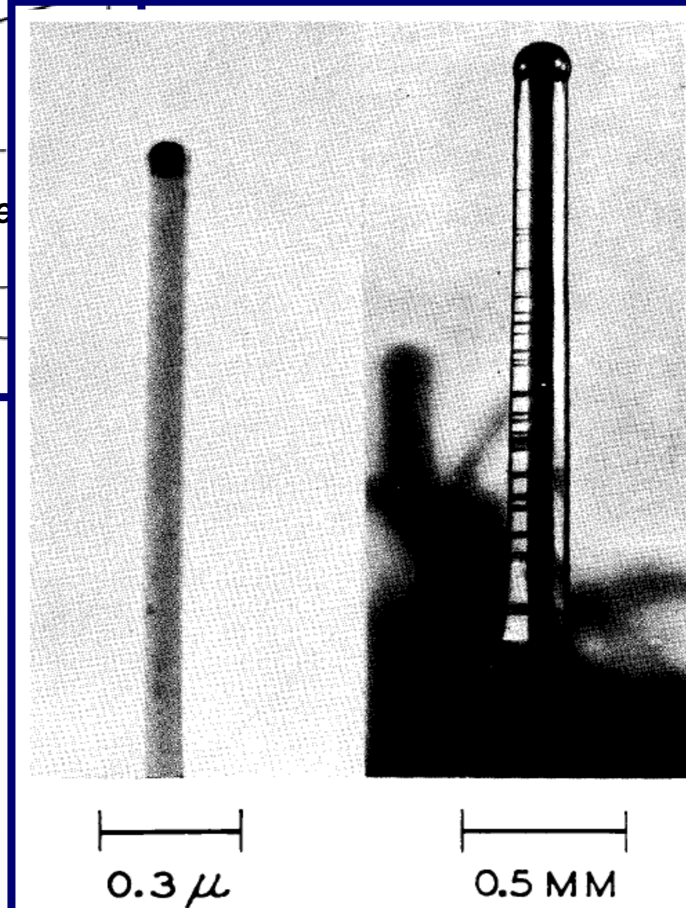
L_D ✪ purity ✪ materials cost

Impure material but high performance

Si Rods by Vapor-Liquid-Solid (VLS) Growth



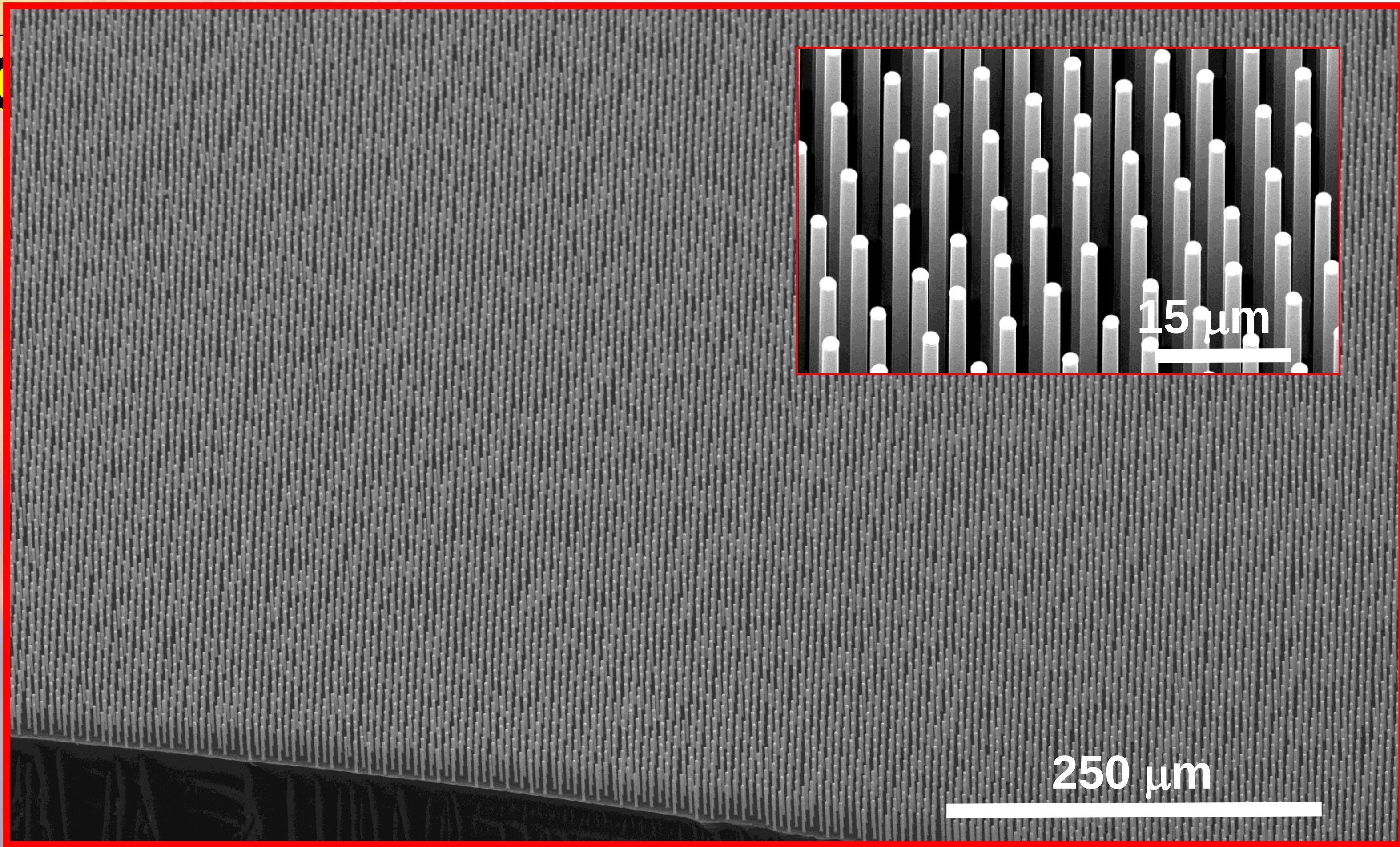




H_2 + $SiCl_4$, ~1000 C

- ***Single crystals***
- ***Growth direction controlled by substrate***
- ***High growth rates (up to microns/s)***
- ***Inexpensive gas phase precursors***

B. M. Kayes, M. A. Filler et al., *App. Phys. Lett.* **91**, 103110 (2007)
R. S. Wagner and W. C. Ellis, *App. Phys. Lett.* **4**, 89 (1964)

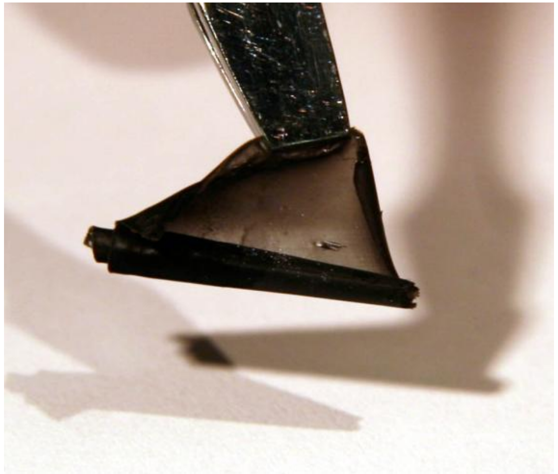


3 μm array, 500 nm Cu, T_{growth} = 1000°C, P_{growth} = 760 Torr, 10 min growth, 2 mole % $SiCl_4$ in H_2

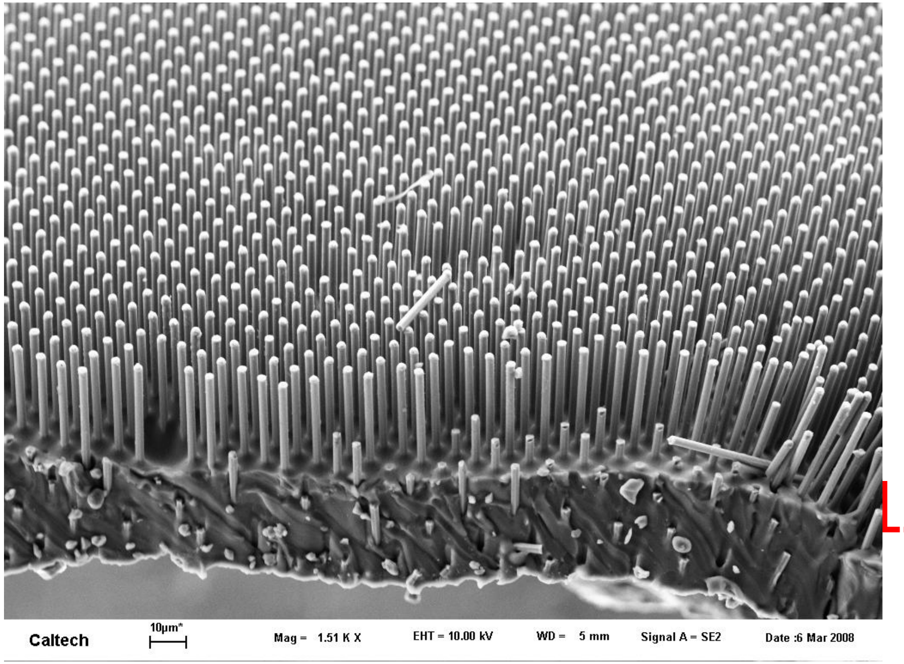
Copper produces wire arrays that are structurally equivalent to gold.

Large Area Rod Array Removal

Top-down view



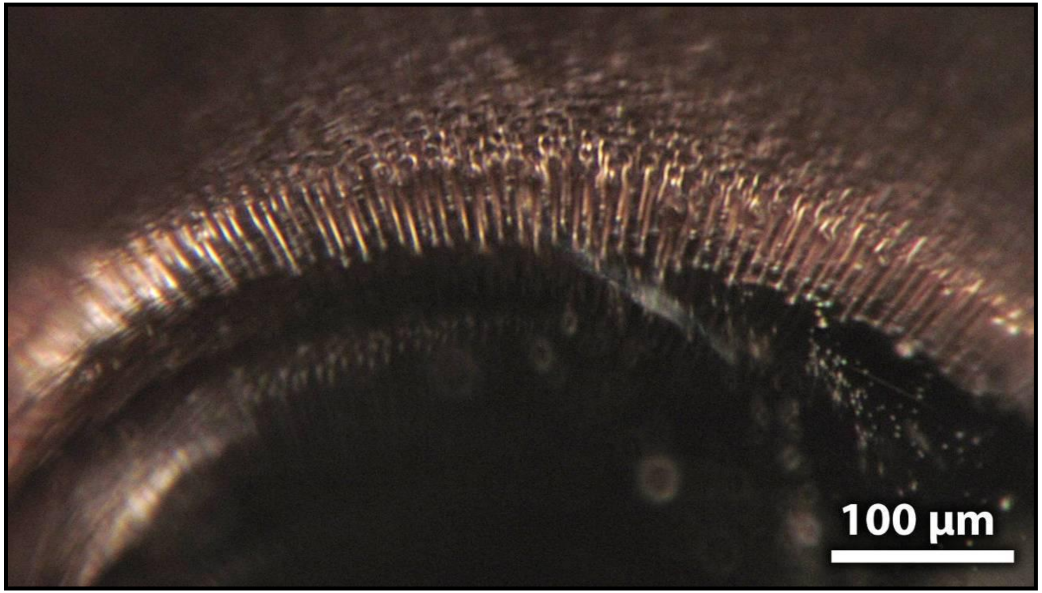
Side view



115 μm

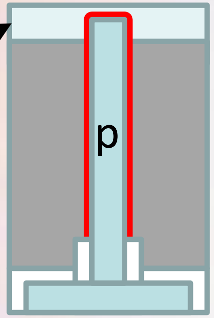
- Large area arrays (> 1 cm^2) transferred in one piece.
- Conformal coating from top to bottom of rods

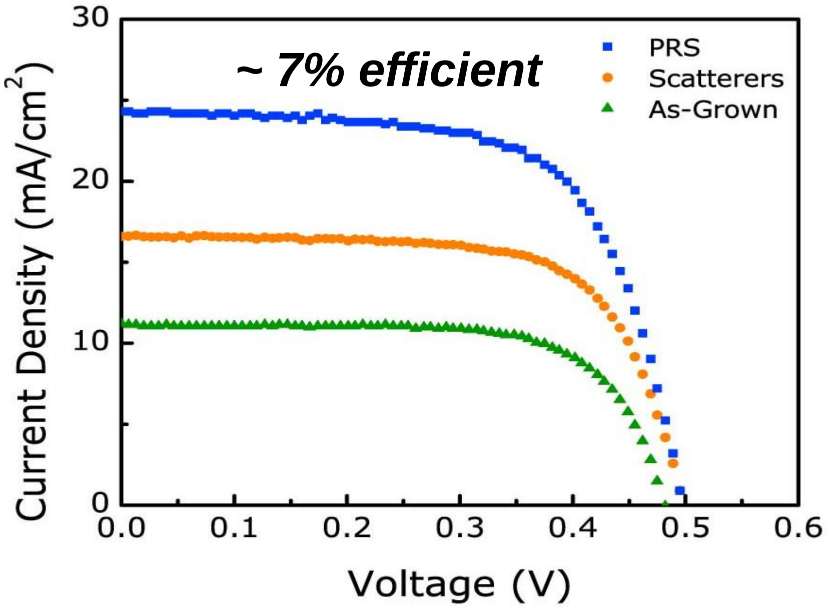
Flexible Inorganic-Polymer Composites

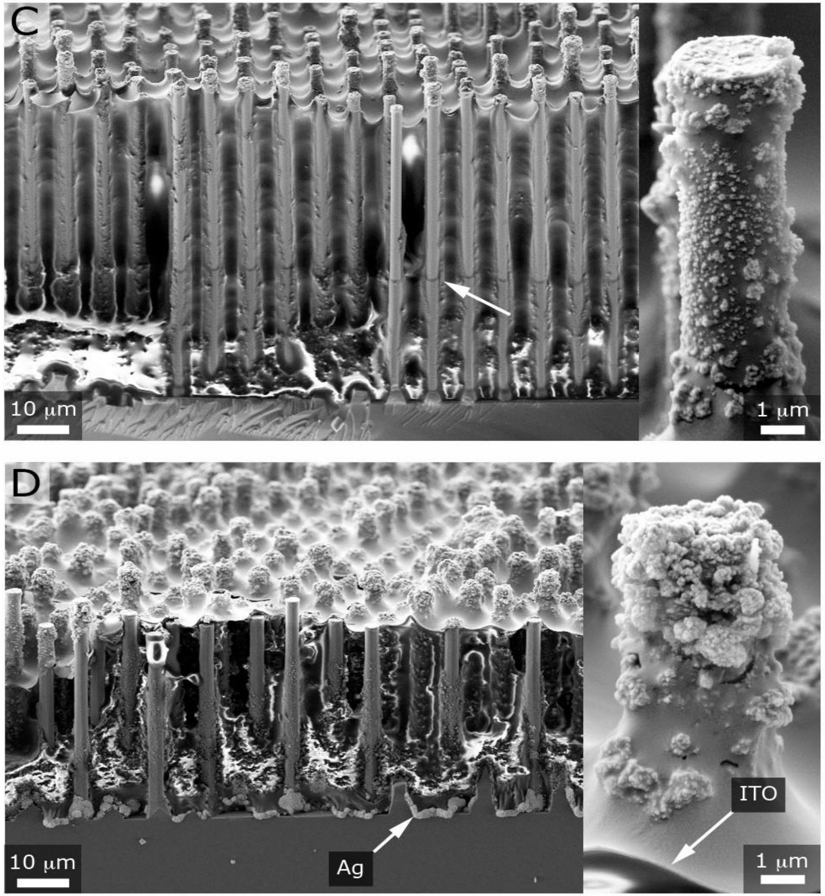


Initial Solid-State PV Devices

Add transparent top contact:

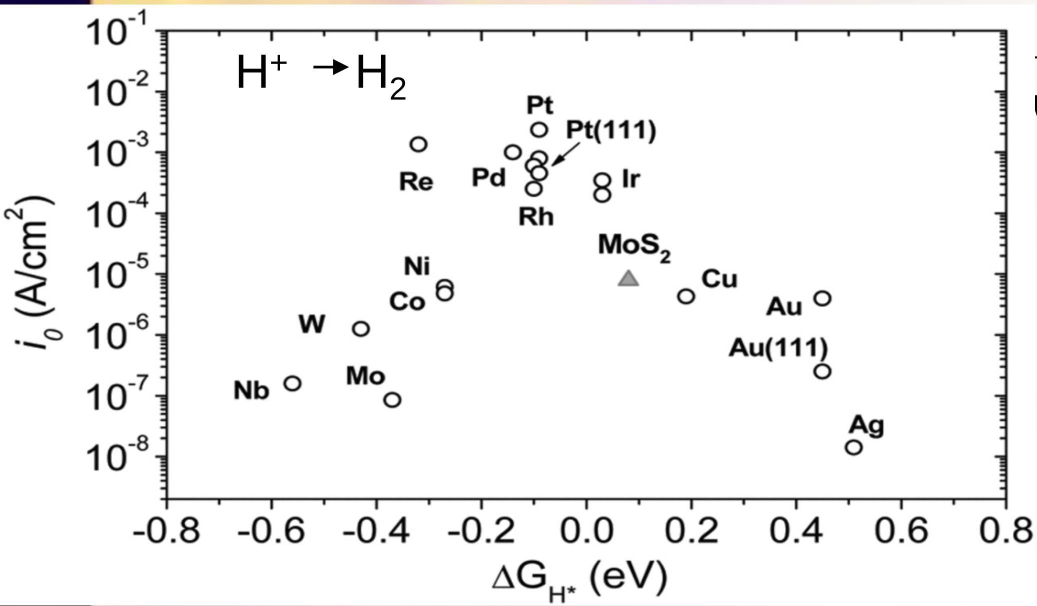


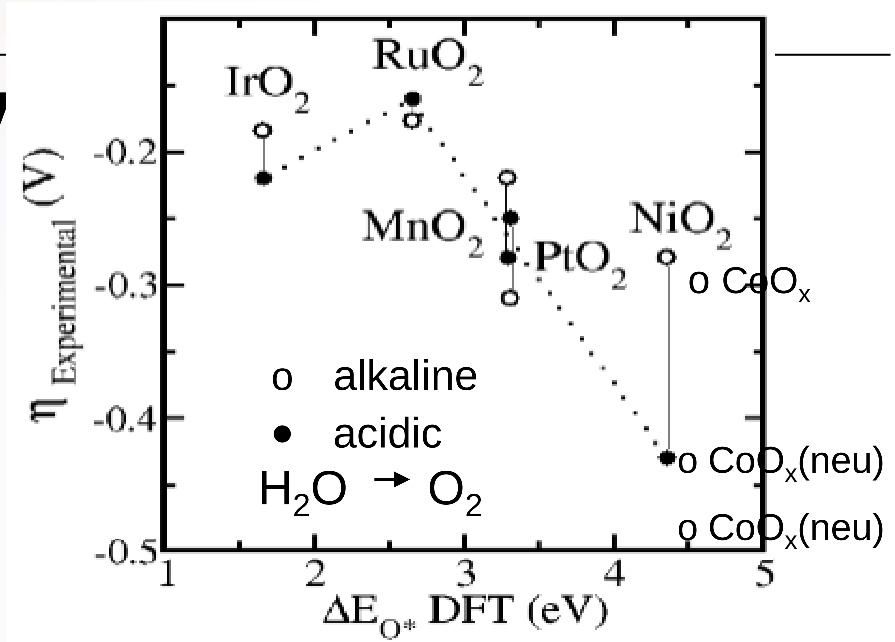


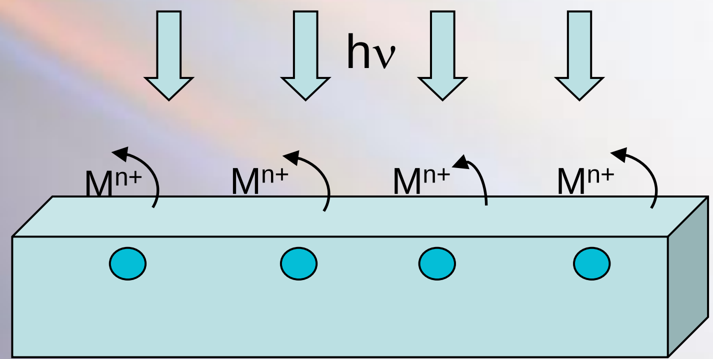


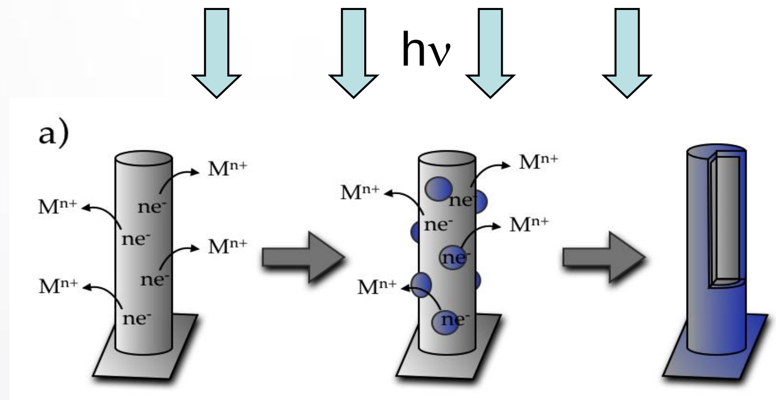
Putnam, Boettcher, et. al. In Prep.

Deep Integration on Nanoscale: New Functionality

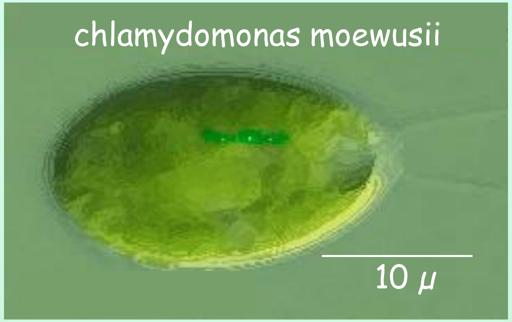


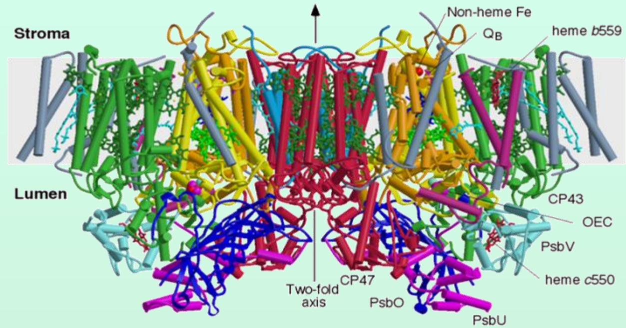


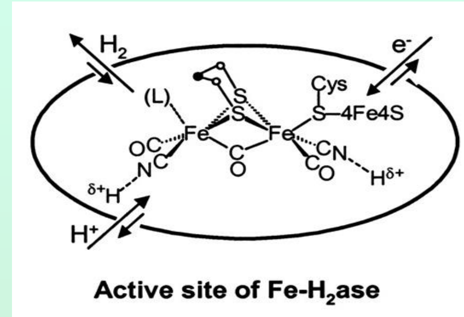




Solar-Powered Catalysts for Fuel Formation





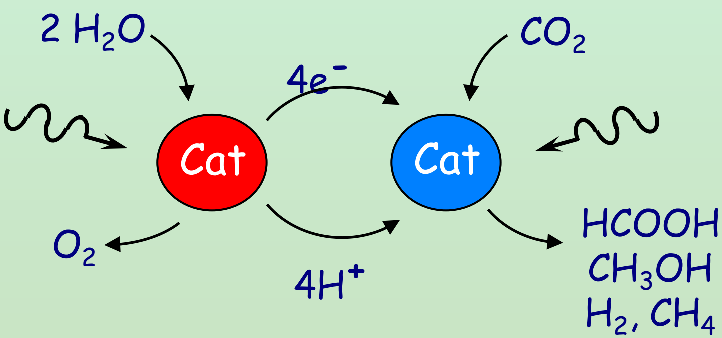


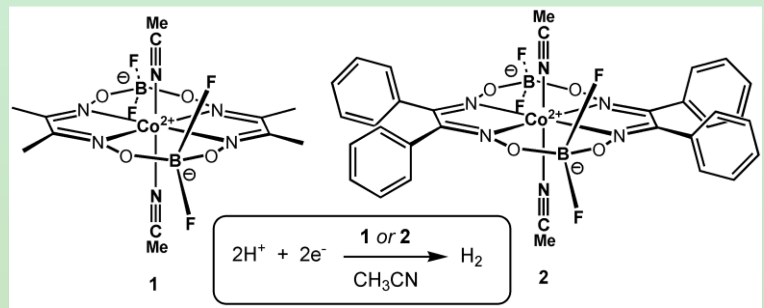
photosystem II

hydrogenase

$2H^+ + 2e^- \Leftrightarrow H_2$

oxidation *reduction*





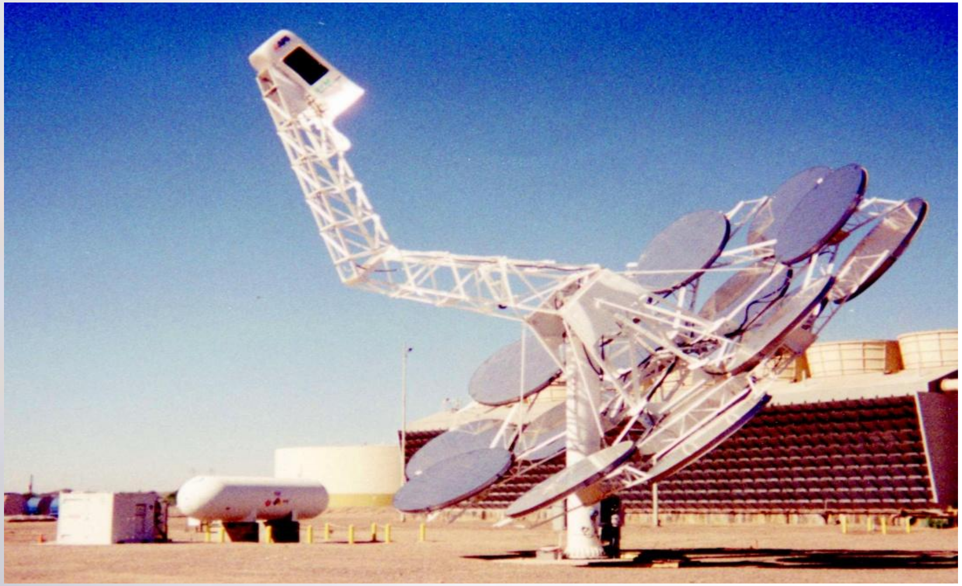
Solar Energy Challenges

Solar electric

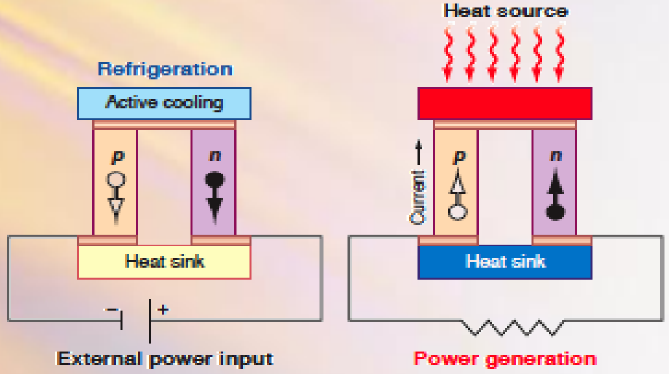
Solar fuels

Solar thermal

Cross-cutting research



Thermoelectric Conversion

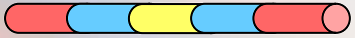


thermal gradient ⇔ electricity

figure of merit: ZT ~ (σ/κ) T

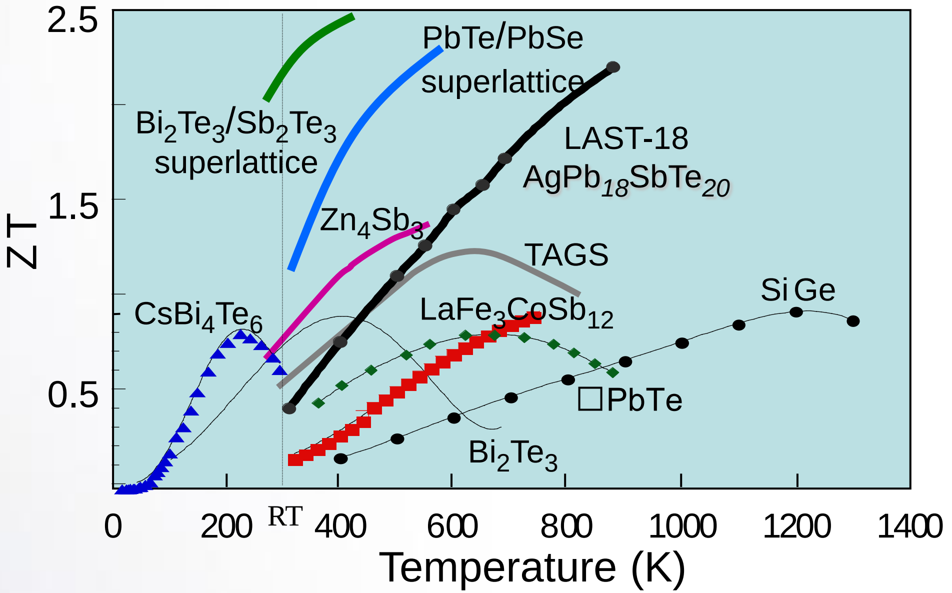
ZT ~ 3: efficiency ~ heat engines
no moving parts

Scientific Challenges
increase electrical conductivity
decrease thermal conductivity



nanowire superlattice

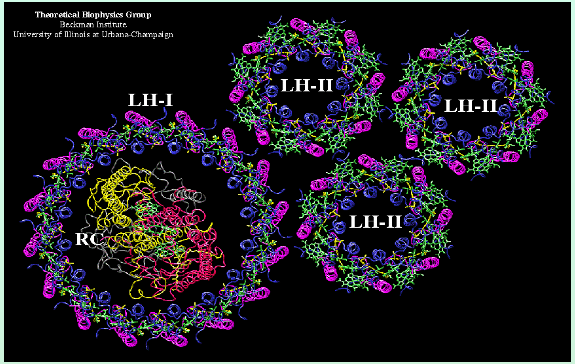
nanoscale architectures
interfaces block heat transport
confinement tunes density of states
doping adjusts Fermi level



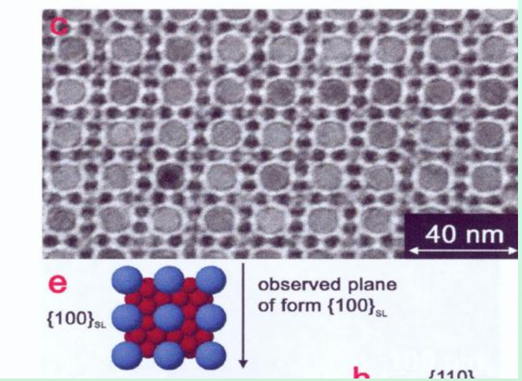
Solar Land Area Requirements

Control of Materials Properties Through Nanoscience

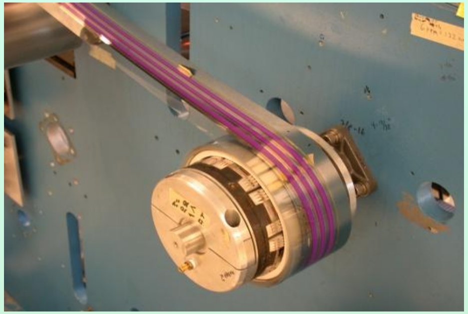
biological



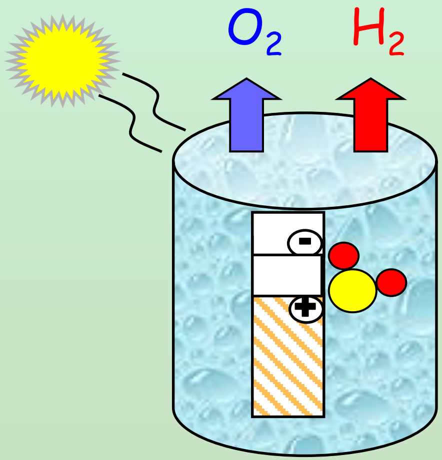
physical



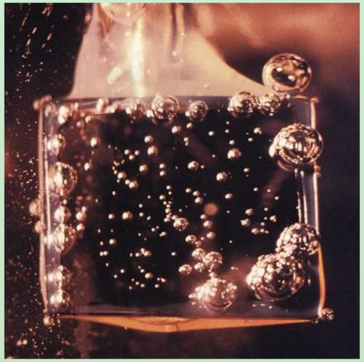
mechanical



Self-assembly of complex structures



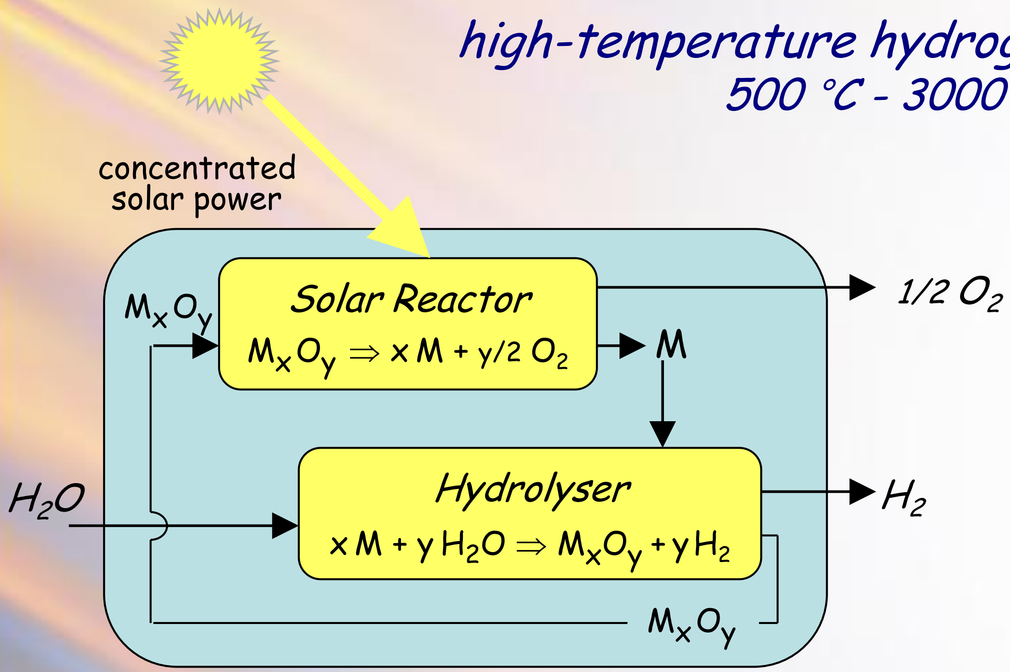
Hydrogen from water and sunlight

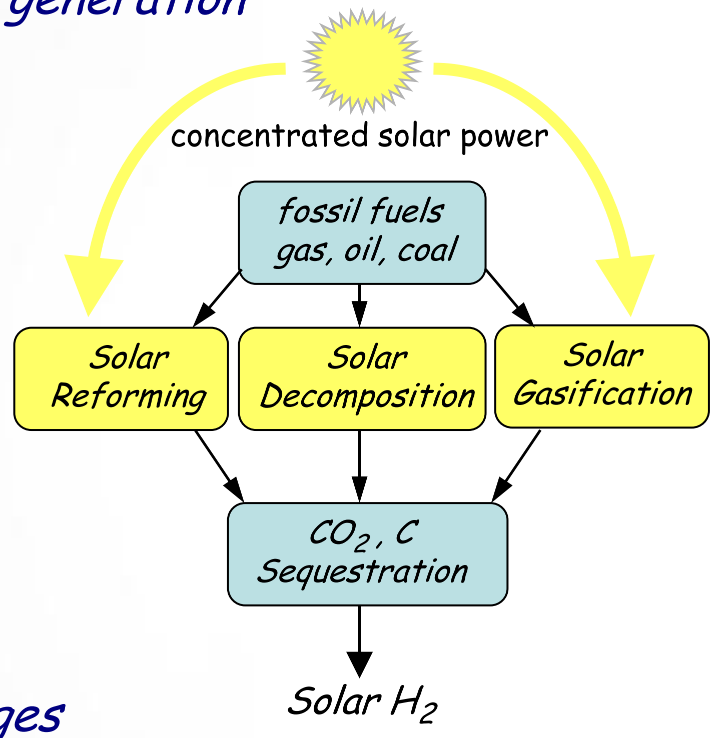


demonstrated efficiencies 10-18% in laboratory

Solar Thermochemical Fuel Production

high-temperature hydrogen generation
500 °C - 3000 °C





Scientific Challenges

high temperature reaction kinetics of
- metal oxide decomposition
- fossil fuel chemistry

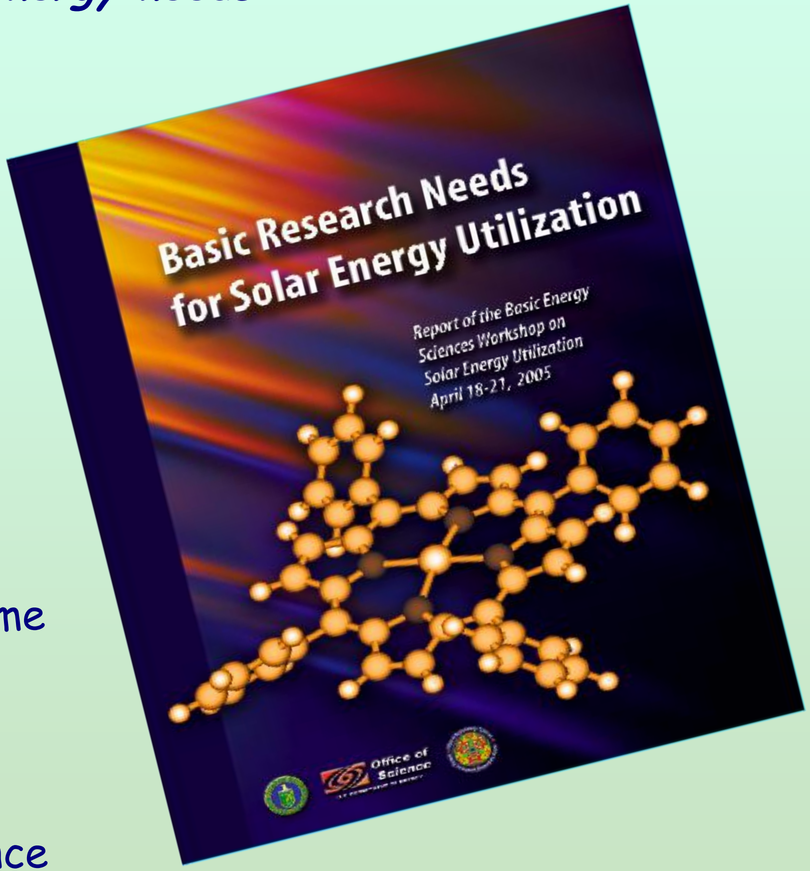
robust chemical reactor designs and materials

A. Streinfeld, Solar Energy, 78,603 (2005)

Basic Research Needs for Solar Energy

- ***The Sun is a singular solution to our future energy needs***
  - capacity dwarfs fossil, nuclear, wind . . .
  - sunlight delivers more energy in **one hour** than the earth uses in **one year**
  - free of greenhouse gases and pollutants
  - secure from geo-political constraints

- ***Enormous gap between our tiny use of solar energy and its immense potential***
  - Incremental advances in today's technology will not bridge the gap
  - Conceptual breakthroughs are needed that come only from high risk-high payoff basic research



- ***Interdisciplinary research is required***
  physics, chemistry, biology, materials, nanoscience

- ***Basic and applied science should couple seamlessly***

Summary

- Need for Additional Primary Energy is Apparent
- Case for Significant (Daunting?) Carbon-Free Energy Seems Plausible (Imperative?)

Scientific/Technological Challenges

- Provide Disruptive Solar Technology: **Cheap Solar Fuel**

Inexpensive conversion systems, effective storage systems

Policy Challenges

- Energy Security, National Security, Environmental Security, Economic Security
- Is Failure an Option? Will there be the needed commitment?

Solar Energy Challenges

Solar electric

Solar fuels

Solar thermal

Cross-cutting research